Can Electricity Powered Vehicles Serve Traveler Needs?

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ABSTRACT

Electric vehicles (EV), Hybrid Electric Vehicles (HEV) or Plug-in Hybrid Electric Vehicles (PHEV) are believed to be a promising substitute for current gas-propelled vehicles. Previous research studied the attributes of different types of EVs and confirmed their advantages. The feasibility of EVs has also been explored using simulation, retrospective survey data, or a limited size of field travel data. In this study, naturalistic driving data collected from more than 100 drivers during one year are used to explore naturalistic driver travel patterns. Typical travel distance and time and qualified dwell times (i.e., the typical required EV battery recharging time between travels as based on most literature findings) are investigated in this study. The viability of electric cars is discussed from a pragmatic perspective. The results of this research show that 90 percent of single trips are less than 25 miles; approximately 70 percent of the average annual daily travel is less than 60 miles. On average there are 3.62 trips made between four-hour dwell times as aggregated to 60 minutes and 50 miles of travel. Therefore, majority of trips are within the travel range provided by most of the currently available EVs. A well-organized schedule of recharging will be capable of covering even more daily travels.

1. INTRODUCTION

Currently the transportation system within the United States relies heavily on petroleum. According to data provided by the U.S. Energy Information Administration (EIA), of the average 18,686 thousand barrels per day of petroleum supplied (2009), 8,831 thousand barrels (approximately 47 percent) were consumed by "motor gasoline" (*1*). Environmental and energy problems become increasingly severe accompanied by this large fuel consumption level. Greenhouse gas emissions, tailpipe pollutants, increasing oil prices, and the deficit of petroleum storage inevitably initiate the urge to search for cleaner and more reliable alternative energy supplies. One of the promising solutions is the development and use of electric vehicles (EVs) - vehicles powered partially or completely by electricity. EV manufacturers and researchers believe that EVs can help solve these problems to a large extent. EVs are automobiles propelled completely or partially by electric motors. The verified benefits of electric cars include a reduction in air pollution and greenhouse gas emissions and less reliance on gasoline.

Despite the advantages of electric cars, a widespread deployment is hindered due to the high cost of the vehicles, a limited life span of batteries, a shortage of public battery recharging facilities, and a limited range/distance within which EVs can drive utilizing batteries. The focus of this study is to examine the driving patterns inferred from naturalistic driving data to facilitate the design of EVs such that the EVs meet the requirements of actual travel. The naturalistic driving data collected during the 100-Car Study conducted by the Virginia Tech Transportation Institute (VTTI) are analyzed to recognize patterns of everyday travel. The time gaps (dwell times) between trips that are required for recharging EV batteries and the distances traveled/driving time between such dwell times are investigated.

In terms of the paper layout the following section provides a brief background of the problem and presents a summary of the literature about the topic. Subsequently, the data used in the analysis are described followed by an explanation of the methodology employed in analyzing the data. Finally, the study conclusions and recommendations for further research are presented.

2. BACKGROUND AND LITERATURE REVIEW

Much research has been conducted describing the advantages of vehicles powered partially or completely by electricity on the environment, the battery recharging access and schedule, the cost of electricity, the savings on gasoline, or the designs of the electric car. Sovacool (*2*) divided cars into four types according to their engine types: 1) Conventional cars use internal combustion engines; 2) Hybrid electric vehicles (HEVs) maintain their batteries at a constant state of charge, and recharging occurs only from regenerate braking kinetic energy or the heat engine; 3) Plug-in HEVs (PHEVs) recharge from outlets, and most of them contain a battery capable of powering a travel distance between 20 and 60 miles. PHEVs can be parallel hybrids or series hybrids depending on the power train configurations; 4) Vehicle-to-grid PHEVs (V2Gs) are similar to PHEVs but can send power back to the grid in addition to the advantages of PHEVs. PHEVs or V2Gs are believed to be more appropriate for future development, either technologically or economically, and therefore so are the EVs referred to in this paper.

Gonder et al. (*3*) used second-by-second global positioning system (GPS) data collected during a 24-hour time period from 227 vehicles in the St. Louis, Missouri, metropolitan area to simulate the operating profiles of conventional, HEV, and PHEV models to assess fuel consumption and operating characteristics of these vehicle technologies. They found that PHEVs consumed less than 50 percent of the petroleum used by conventional cars. In a study conducted by Heffner et al. (*4*), the Toyota Prius-based PHEV was reported to achieve fuel efficiency from 65 to 95 miles/gallon.

Although EVs provide advantages and technologies that have enabled longer battery ranges, electric cars are not as popular as the designers and car manufactures hope. The size and cost of batteries for EVs hinder the acceptance of EVs by a wider population. The larger EV batteries are, the longer all-electric-range (AER) the EV can be powered.

However, the cost of EVs also increases accordingly when the battery size gets larger. A smaller battery can help decrease the cost but requires more accessible recharging locations and a greater frequency of recharging. The key point is to balance the battery range capability, the cost of the battery and maintenance, and the cost of electricity. The successful design of EVs should satisfy the requirements of EV users for their everyday travel at an affordable price.

To better understand the needs of potential EV users, Kurani et al (*5*) endeavored to identify the EV attributes that users value most using survey data. They concluded that the PHEV potential users are primarily interested in a larger all-electric travel range and are secondarily interested in increased gasoline fuel economy. In contrast, Axen and Kurani (*6*) conducted an Internet-based survey of 2,373 households buying new vehicles to discover the answers to three questions: 1) How many households have regular access to battery recharging opportunities? 2) Where and when is recharging possible? and 3) What PHEV designs currently appeal to consumers? Approximately 60 percent of survey participants were able to locate at least one viable recharging location during a 24-hour diary day. At least one-half of participants were already equipped for at-home battery recharging. The most frequently chosen upgrade option selected by the participants was "the gasoline fuel economy in Charge Sustaining (CS) mode." The research results of Kurani et al and Axen and Kurani are based on the users' views of their preferences for EVs and mostly on the conception of, "What I want the car to be like IF I have one." To further facilitate the design of EVs, it is therefore necessary to analyze peoples' actual travel patterns.

Karlsson (*7*) studied car movement data from 30 families for approximately two weeks. Combined with the results from a Monte Carlo analysis, he concluded that the size of PHEV batteries is a crucial factor in the design of electric cars, and the design is highly dependent on the movement pattern of cars. According to Winkel et al.(*8*), the average amount of travel time of a vehicle is approximately 1.3 hours. This number is relatively constant regardless of density of population. Vyas et al. (*9*) used the 2001 National Household Travel Survey (NHTS) data (*10*) (total of 142,111 trips made by 32,022 vehicles recorded) and vehicle data from the 2005 American Housing Survey to identify the share of vehicle miles traveled (VMT) that can be completed with an EV. A vehicle simulation model, Powertrain System Analysis Toolkit (PSAT), was used to simulate PHEV power train configurations and to analyze the differences of different PHEVs. Vyas et al.(*9*) concluded that it is more desirable to develop a diverse portfolio of PHEV Charge Depleting (CD) capabilities to meet various customer needs. Due to the limitation of NHTS data, which are based on retrospective information from participants and may omit some trips and contain errors in travel time/dwell time information, the research conducted by Vyas et al.(*9*), though very informative, has yet to be expanded to reflect a more accurate pattern of real-life travels.

Therefore, it is now urgent to assemble statistical data about the movement patterns of potential EV users in their everyday travels for the future design of EVs. For example, how long do people normally travel before they have enough of a dwell time period to recharge the electric cars? How often do drivers have dwell times that satisfy the minimum time required to recharge a car? What is the minimum AER required? In this research, naturalistic driving data collected in the VTTI 100-Car Study (*11*) will be analyzed to answer such questions.

3. DATA DESCRIPTION

According to a report from the Second Strategic Highway Research Program (SHRP 2) L10, there are several naturalistic driving data sets accessible to the authors, including the Automatic Collision Avoidance System (ACAS) Field Operational Test (FOT) and the Road Departure Crash Warning System (RDCWS) FOT conducted by the University of Michigan Transportation Research Institute (UMTRI) and the 100-Car Study, the Drowsy Driver Warning System (DDWS) FOT, the Naturalistic Truck Driving Study (NTDS), and the Naturalistic Teenager Driving Study (NTNDS) conducted by VTTI (*12*).The 100-Car Study data set was selected for this research because of the typical driver age, occupation, gender distribution, and data size.

The 100-Car Study recruited 109 primary drivers in Northern Virginia to have their vehicles instrumented or to receive a leased vehicle. Northern Virginia consists of several counties and cities and is a widespread region with about 2.6 million residents. It is the highest income region of Virginia and has six of the 20 highest-income counties in the nation. Primary drivers are those who signed the data collection contract with VTTI. Drivers were recruited by placing flyers on vehicles or by placing classified announcements in local newspapers. The data collection lasted for approximately 18 months (12 to 13 months per vehicle). In the majority of the cases, there were other drivers who drove the equipped vehicle. Consequently, the resulting data set included driving data from 257 primary and secondary (additional) drivers. Secondary drivers were usually friends or family members of the survey participants. The area that the survey participants traveled covered Washington, D.C., Maryland, Delaware, New York, etc. in addition to the state of Virginia.

Drivers were given no special instructions; those who had their private vehicles instrumented received $125 per month and a bonus at the end of the study for completing necessary paper work. Drivers who received a leased vehicle received free use of the vehicle, including standard maintenance, and the same bonus at the end of the study for completing necessary paperwork. The majority (78 out of 109) of the drivers drove their personal vehicles. The data set included 6.4 Terabytes (TB) of approximately two million VMT from 257 primary and secondary driver participants. Continuous video was collected on four channels at 30 Hz: driver's face, instrument panel, forward roadway, and rear roadway. Vehicle network information (speed, brake pedal, throttle, turn signal); GPS (latitude, longitude, heading); and X, Y, and Z acceleration were also collected. Forward and rear radar were used to collect surrounding information. Supplementary information, such as demographic data, home and work addresses, accident history, etc. were also collected for the primary drivers.

Since there is no supplementary information for the secondary (additional) drivers, their data were not included in this research. Driving data from 108 primary drivers (one driver has invalid data) were used in the analysis. Out of the 108 drivers, 40 percent of them are females. The age span ranges from 18 to 65 years old. The goals of the 100-Car Study were to examine crashes/near-crashes and associated driver behavior.

Therefore, the study aimed at deliberately selecting participants that drove more than average and were more prone to experiencing safety-related events. The targeted goal was to recruit 60 percent of young drivers under the age of 25. The resulting age distribution is shown in TABLE 1(*11*). Approximately one-half of the participants lived less than 20 miles away from their workplaces. The distribution of distances from home to work of the participants is shown in FIGURE 1.

Table 1: Age Distribution of the 100-Car Study Participants

Age	Female (Number/Percentage)	Male (Number/Percentage)	Total
18-20	9 (8.3%)	7 (6.4%)	16 (14.7%)
21-24	11 (10.1%)	10 (9.2%)	21 (19.3%)
25-34	7 (6.4%)	12 (11%)	19 (17.4%)
35-44	4 (3.7%)	16 (14.7%)	20 (18.4%)
45-54	7 (6.4%)	13 (11.9%)	20 (18.3%)
55+	5 (4.6%)	8 (7.3%)	13 (11.9%)
Total	43 (39.4%)	66 (60.6%)	109 (100%)

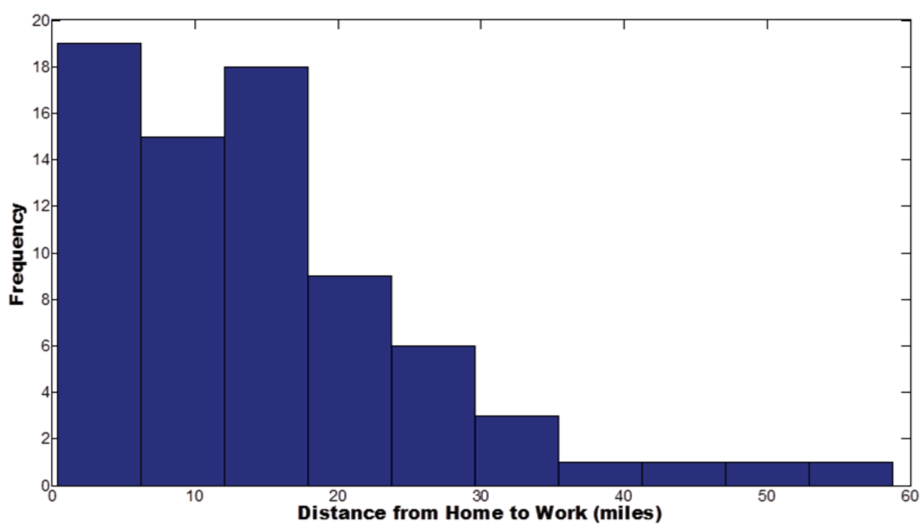


Figure 1. Distance to work frequency distribution.

4. METHODOLOGY AND DATA ANALYSIS

The Data Acquisition System (DAS) in the 100-Car study collected GPS data at a frequency of 10 Hz, and the original data set contained more than 1.73 billion records. Data were organized by file, which is the storage unit of the DAS. In the majority of the cases one file comprised one trip. There are circumstances in which multiple trips such as trip chains were recorded in one file or when one trip was too long and the database manager cut the trip into multiple files. While a typical single trip (recorded as one file) should have speed variations as shown in FIGURE 2 (a), one file containing multiple

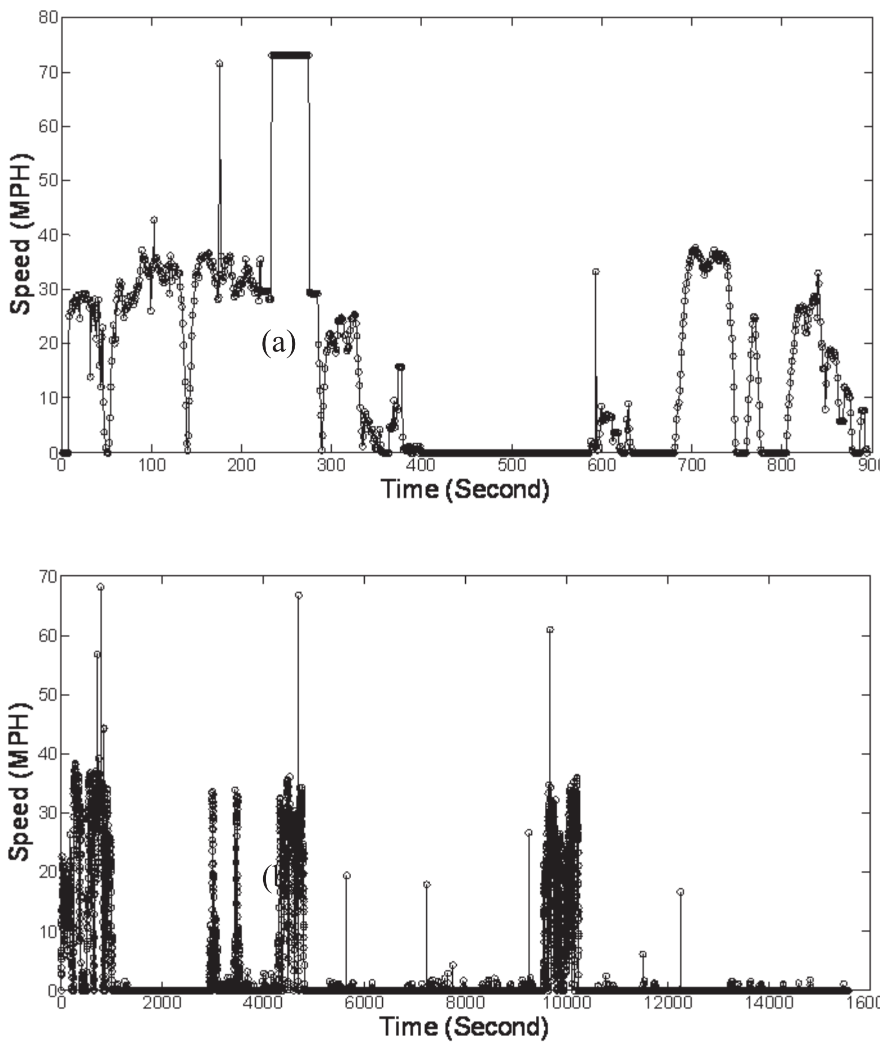


Figure 2. Speed profiles of (a) typical file (b) 4.5-hour-long file with multiple trips.

trips as shown in FIGURE 2 (b) has multiple long periods of continuous zero speeds between each trip. Since the trip length of each individual trip itself is not the focus of this study, the data processing procedure to identify trip ends was simplified. For the case when one file contains multiple trips, the file was divided into trips based on the speeds. For the case when one trip was recorded in multiple files, it was found that the time gaps between those files were usually very short. This often happened when the trip was either part of a trip chain with multiple brief stops or the signal loss caused the closure of one file recorded by the DAS and started a new file. In either circumstance, this type of error will not affect the results of this analysis because only time gaps that are long enough to be used to recharge EVs are analyzed in this study. Short breaks will be ignored regardless of the reason as to why they were generated.

There were no distance traveled data documented in the 100-Car raw data set for each individual file/trip except the total mileage driven by the participants as recorded by odometers. Therefore, the longitude and latitude were used to calculate the distance a car traveled in each particular trip using Equation (1) (*13*).

$$Dist_j = \sum_{i_j=1}^{n_j-1} \sqrt{69.1 * (Lat_{i_j+1} - Lat_{i_j})^2 + 53 * (Long_{i_j+1} - Long_{i_j})^2} \qquad (1)$$

Where $Dist_j$ = total distance of trip j;
n_j = total number of GPS points recorded during trip j;
Lat_{ij+1} = the latitude of the $i + 1^{th}$ GPS point of trip (degrees); and
$Long_{ij+1}$ = the longitude of the $i + 1^{th}$ GPS point of trip j(degrees).
MatLab codes were developed to compute the distances traveled. The resulting cumulative distribution of trip lengths and the travel times of all 136,616 trips are plotted in FIGURE 3. Trip lengths in terms of time (minutes) and distance (miles) are both presented here for comparison purposes. The majority of the trips (90 percent) were less than 25 miles. More than 95 percent of the trips were accomplished in one hour. One-half of the trips were less than 20 minutes or 10 miles.

Using Equation (2), the average annual daily trip length and trip time for each driver is calculated, and the results are plotted in FIGURE 4. As can be seen, approximately 70 percent of the average annual daily travel is less than 60 miles, and one-half of the daily trips are less than 50 miles or 1.5 hours. This information is comparable to the results from NHTS 2001, which indicate that 50 percent of average traveling distance is less than 24.8 miles/day and 70 percent of traveling distance is less than 35 miles/day (*14*).

$$\frac{\sum_{j=0}^{d_i} Dist_{ij}}{d_i} \quad \forall\, Driver\ ID = i, i = 1,2,3 \ldots 108 \qquad (2)$$

Where $Dist_{ij}$ = distance traveled by driver on day; and d_i = the number of days driver i participated in the study.

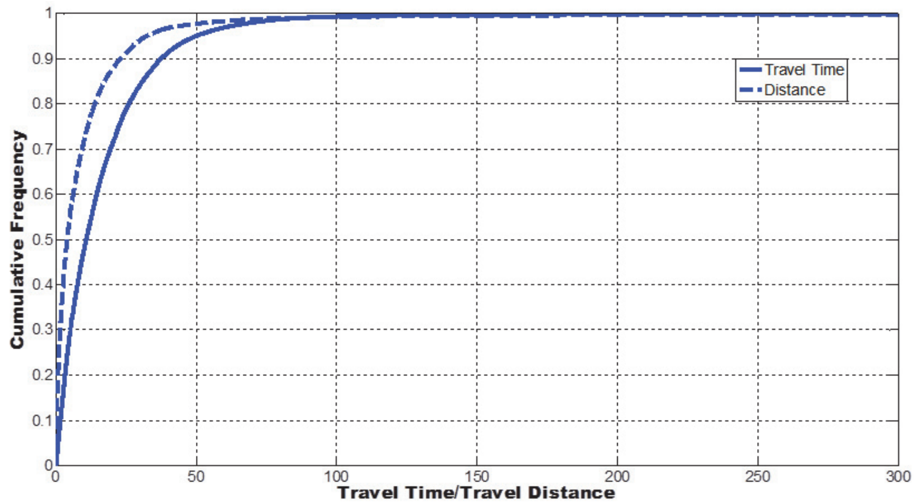


Figure 3. Travel time and distance of individual trips.

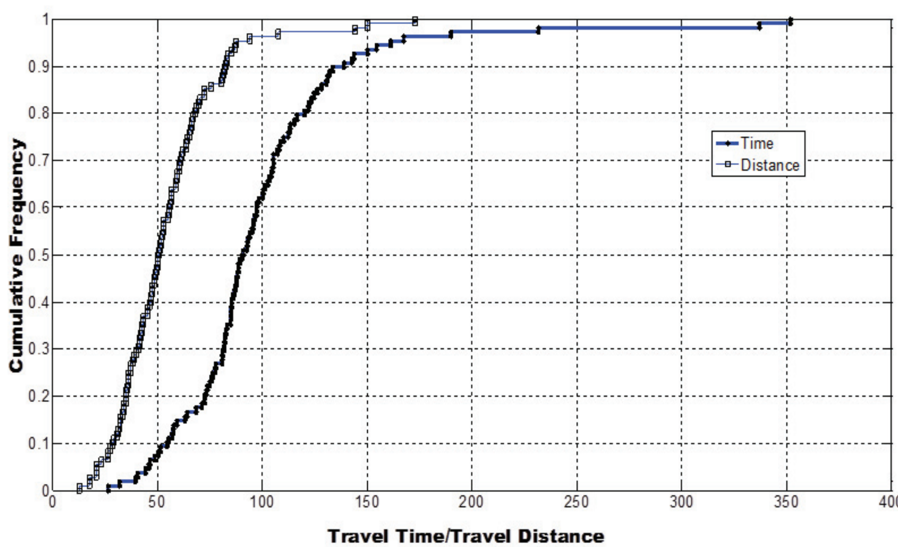


Figure 4. Annual average daily travel time/distance.

The distribution of travel times and trip lengths proves that many routine trips are short and are highly possible to be powered by EVs. Based on data presented in FIGURE 4, currently available PHEVs that usually propel the vehicles up to 40 miles solely by electricity can cover up to 30 percent of the daily trips if the vehicle recharges only once. If the vehicle has recharging opportunities in the middle of the day at appropriate times, 90 percent of the daily trips (80 miles) can be powered by batteries only. Hence, if a qualified dwell time that is long enough to recharge the EVs is available for most drivers during the day, using an EV to replace a gas-powered vehicle is promisingly possible.

A qualified dwell time can last as long as eight hours or as short as one hour or less depending on the battery recharging level and voltage of the outlet. Davies and Kurani (*15*) tested the Toyota Prius hybrid vehicle in their study. The vehicle can be recharged using a standard 110- to 120-volt and 10-A household outlet. A fully discharged battery will recharge completely within five to six hours. The Tesla Roadster can travel 245 miles (394 km) per charge, and it needs to be charged from a 220-volt, 70-A outlet in approximately 3.5 hours (*15*). A high speed charging from three-phase industrial outlets can recharge batteries to 80 percent within approximately 30 minutes. Since current industrial outlet recharging stations are not realistic, only recharging from household electricity voltage is considered in this study. The approximate minimum recharging time based upon findings from the literature is three hours on household electricity voltage. The travel times and distances between qualified dwell times are calculated starting from 180 minutes to 720 minutes in increments of 60 minutes. The number of trips between possible charging times varies from three to eight. The relatively larger standard deviations indicate varied travel patterns of different drivers. Results are listed in TABLE 2.

Table 2: Travel between Qualified Recharging Time Gap

Dwell Time (minutes)	Mean # of Trips Between Recharging	Median # of Trips	Standard Deviation
180	3.19	2	3.75
240	3.62	2	4.09
300	4.00	3	4.37
360	4.29	3	4.57
420	4.53	3	4.80
480	4.87	4	5.12
540	5.45	4	5.76
600	6.23	5	7.06
660	7.07	5	8.96
720	8.02	5	11.07

All trips are aggregated into segment travel distance or travel time between qualified dwell times. The segment travel distances or times are accumulated using (3) and (4) until the dwell time is longer than the pre-set potential recharging. Detailed results for segment traveling between each dwell time tested are listed in TABLE 3. In the table, the mean, median, and 75 percentile of travel length (in terms of travel time and travel distances) are listed by different dwell times, varying from three hours to 12 hours. As can be seen, the longer the dwell time, the less the travel segments but longer the travel lengths increases, which indicates a longer request for electric ranges. The resulting distribution of segment travel distances and times for dwell times of three hours, six hours and 10 hours are plotted in FIGURE 5 through Figure 7, respectively.

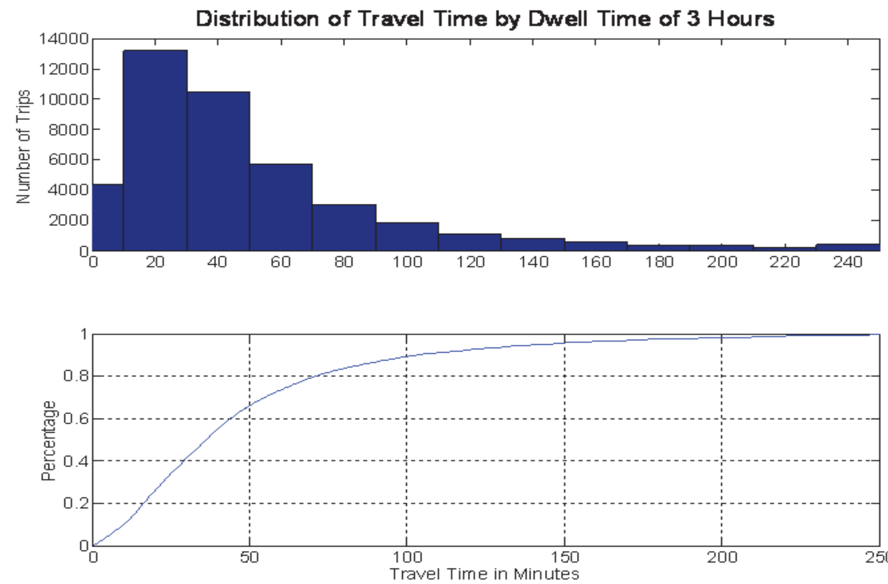
$$AggDist_m = \sum Dist_j \text{ , } \forall TG_{j+1} < Qualified\ Dwell\ Time \tag{3}$$

$$AggTT_m = \sum TT_j \text{ , } \forall TG_{j+1} < Qualified\ Dwell\ Time \tag{4}$$

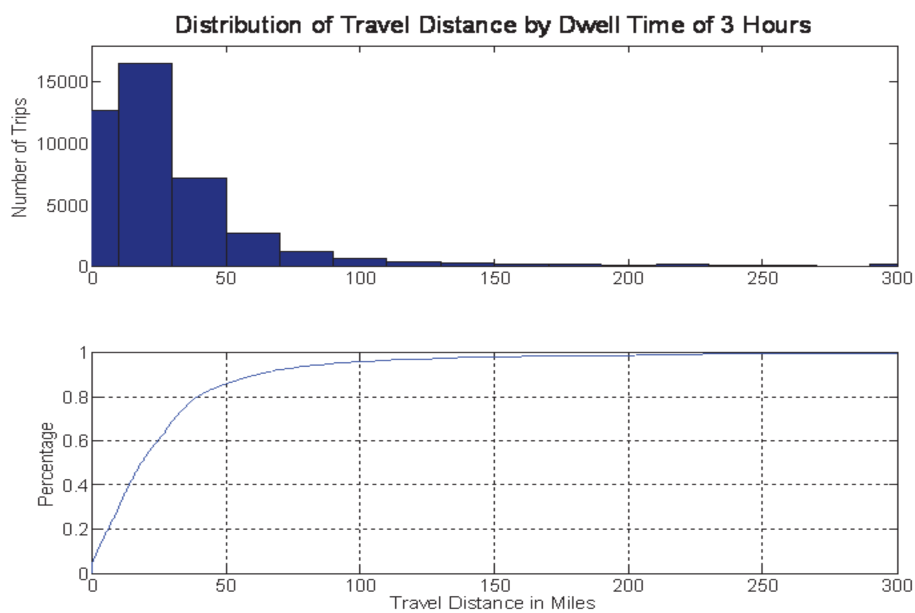
Where $AggDist_m$ is the aggregated travel distance for segment m;
$AggTT_m$ is the aggregated travel time for segment m;
TG_{j+1} is the time gap between trip j and $j + 1$;
$Dist_j$ is calculated by (1; and
TT_j is the travel time recorded by the DAS for trip j.

Table 3: Segment Travels by Dwell Time

Dwell Time (min)	Travel Segments	Mean TT (min)	Median TT (min)	75 % (min)	STD TT	Mean Dist (mi)	Median Dist (mi)	75 % (mi)
180	42799	53.10	36.57	63.56	61.59	44.83	18.59	35.08
240	37750	60.22	40.99	72.79	66.78	50.82	21.60	39.06
300	34194	66.49	44.87	83.20	71.20	56.11	24.35	44.40
360	31857	71.37	48.34	91.44	74.68	60.22	26.60	49.34
420	30138	75.44	51.59	97.10	78.22	63.66	27.58	53.14
480	28062	81.02	56.70	104.65	83.73	68.37	29.47	57.51
540	25046	90.77	66.95	116.95	93.98	76.60	33.73	63.48
600	21946	103.60	76.98	128.85	115.23	87.42	37.84	70.35
660	19325	117.65	83.22	142.78	142.33	99.28	42.27	76.89
720	17031	133.49	87.43	159.68	171.84	112.65	45.03	86.19

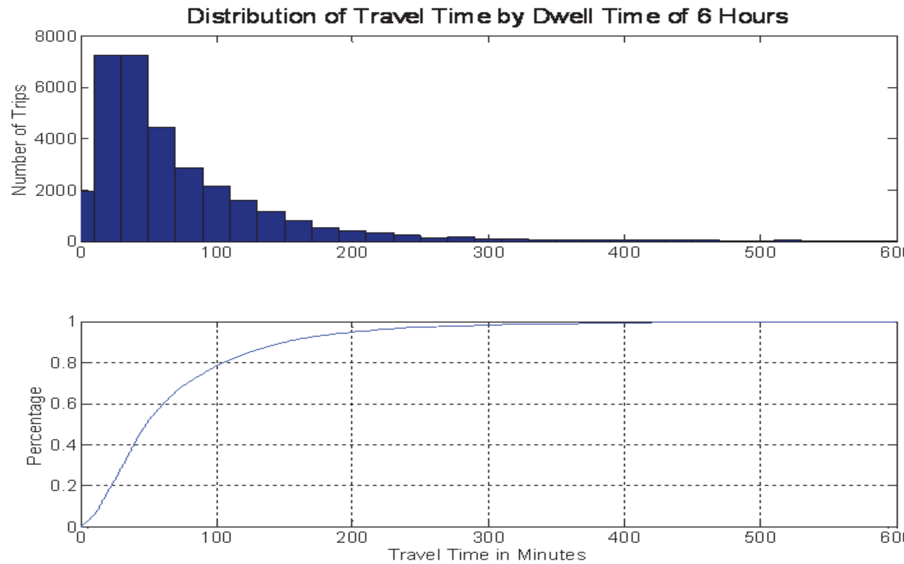


(a)

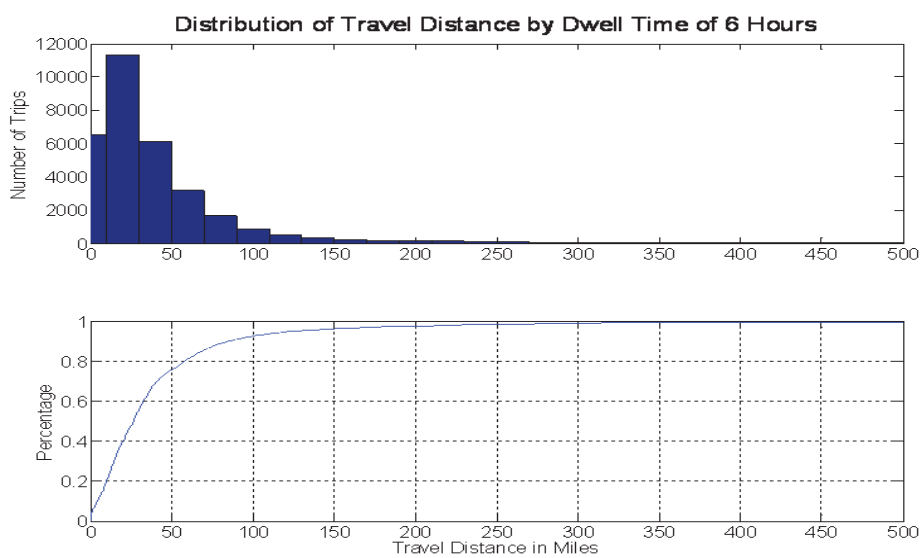


(b)

Figure 5. Travel Time Distribution (a) and Distance Distribution (b) at the Dwell time of Three Hours.

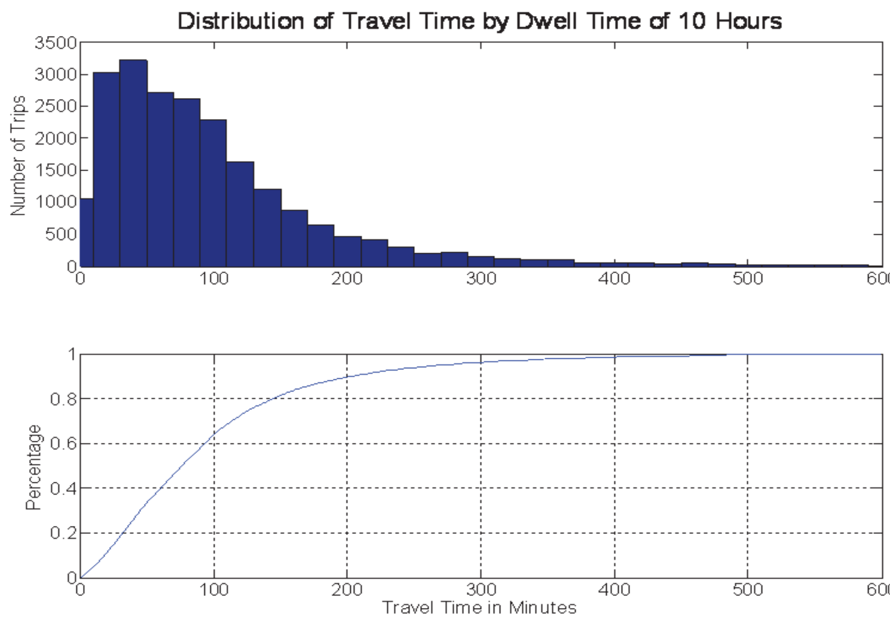


(a)

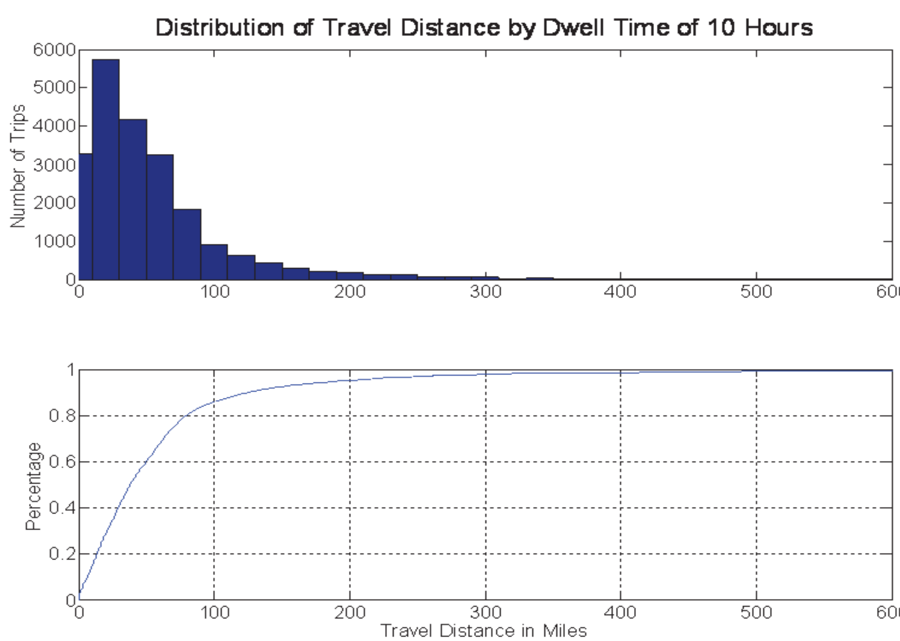


(b)

Figure 6. Time Distribution (a) and Distance Distribution (b) at the Dwell Time of Six Hours.



(a)



(b)

Figure 7. Time Distribution (a) and Distance Distribution (b) at the Dwell time of Ten Hours.

As can be seen in TABLE 3, the median travel distance between a four-hour dwell time is 21.6 miles. It indicates that if a recharging station is available both at home and in public, half of the traveling can be powered by batteries of currently available PHEVs, which can support 20 to 40 miles of travel exclusively by batteries. Even if the recharging access is only available at home and assuming a dwell time of 10 hours indicates an overnight parking at home, one-half of travels are still within the 40-mile electricity powered traveling coverage (the median travel distance between a dwell time of 10 hours is 37.84 miles). However, if the goal of designing an EV to power the majority of travels (e.g., 75 percent of the trips) and the battery charging stations are only available after the vehicle is driven back home, the EVs need to power approximately 75 miles of driving. Again, the large standard deviation values indicate a large variation of travel patterns from driver to driver.

5. REGENERATING ENERY

One popular category of electric vehicles is the hybrid electric vehicles, e.g. the type of cars that can recapture significant amounts of energy during braking and reuse it. The amount of braking during normal driving is of interest of this research because it has a direct impact on the efficiency of hybrid electric vehicles. A closer examination of the 100-Car data does reveal a significant portion of braking during normal driving.

Of the total more than 134,900 trips in this dataset, equivalent to about 37,000 hours of driving, there is more than 40% of the total driving time that drivers were stepping on the braking pedals. Most hybrid electric vehicles manufacturers claim that 90% of the mechanical energy can be converted and captured by regenerative braking. Therefore, the energy saved will be significant (*16*) during normal driving.

To further examine the detailed decelerations, the braking rates are plotted in Figure 8, which shows a CDF plot of median braking rate of all the trips. As can be seen from the figure, about 35% of the median deceleration rate is at least 0.05 g. Figure 9 plots the median, 75th percentile, and 90th percentile of the deceleration rates.

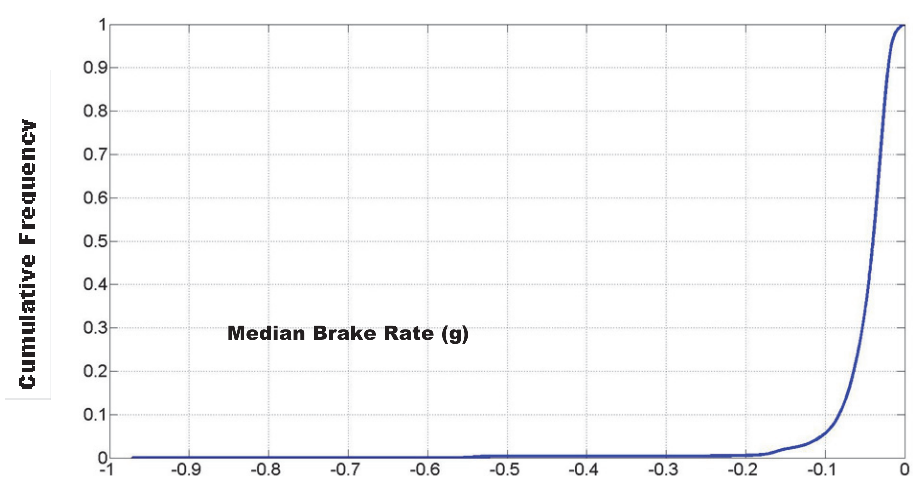


Figure 8. CDF of the Median Brake Rate (g)

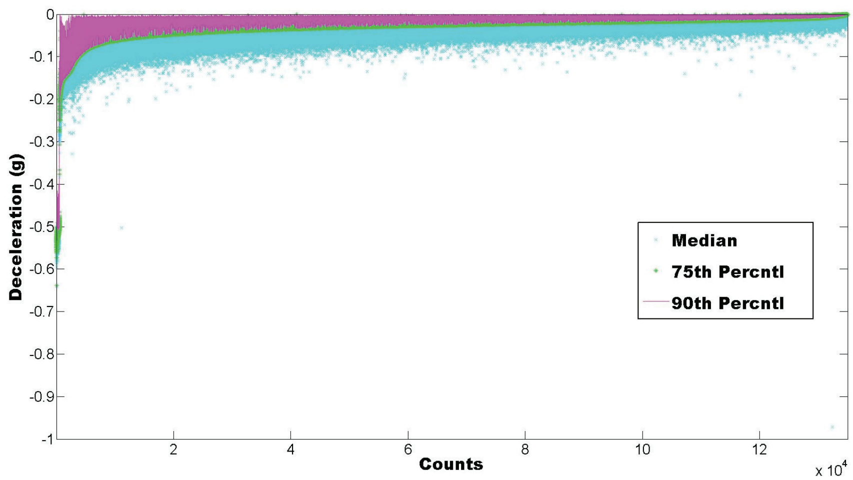


Figure 9. Deceleration Rates (g)

6. CONCLUSIONS AND DISCUSSIONS

This study uses GPS data collected during the 100-Car Naturalistic Driving Study to characterize the travel patterns of drivers in the Northern Virginia and D.C. areas to provide suggestions for the design of EVs. Based on the studies of aggregated travel distance and travel time between qualified dwell times, the authors find that the currently available PHEVs are capable of powering at least 30 percent of daily travel exclusively by batteries without recharging during the day. When the EVs cannot be recharged fully, it is still possible to use EVs as a regular transportation vehicle. The fact that 90 percent of a single trip is less than 25 miles makes it possible to recharge partially during shorter dwell times to support shorter trips. The travel patterns of drivers vary significantly as can be seen from the large standard deviation values. Therefore, the design of batteries for EV needs adjustments according to the different needs of different users.

As stated before, since the participants of the 100-Car Study were recruited for the purpose of safety studies, the drivers were deliberately selected such that they tend to drive more than regular drivers. The participants were inquired about their typical travel distances before they were recruited for the 100-Car Study. The self-reported annual miles traveled are shown in TABLE 4. Also listed in TABLE 4 are the survey results from NHTS 2001 (*10*). Interestingly, the self-reported mileages from the two studies (i.e., NHTS 2001 and the 100-Car Study) are not consistent. The participants from the 100-Car Study claimed much longer travel distances than the survey participants from NHTS 2001. Possible reasons may include the desire of 100-Car Study participants to qualify themselves in the study and the resulting exaggeration of their travel distances. While the resulting total actual miles driven during the 100-Car Study are aggregated in comparable bins, the results are more similar to the results from NHTS 2001. The "Not Specified" category in NHTS 2001 accounts for a large percentage — 20 percent of participants did not specify their travel distances. If distributing this 20 percent to the other distance categories, the travel pattern of NHTS 2001 participants will be more consistent with the results from the 100-Car Study. Therefore, the data from the 100-Car Study appear to be representative of the entire population.

Table 4: Comparison of Travel Lengths

	Travel Distance (miles)	**< 15 k**	**15 k~25 k**	**25 k**	**Not Specified**	**Grand Total**
Data Source	100-Car Study (Self-reported)	9 (8%)	82 (76%)	2 (15%)	1 (1%)	109 (100%)
	100-Car Study (Aggregated from data)	63 (58.3%)	40 (37%)	5 (4.7%)		108 (100%)
	NHTS 2001	11,322 (54%)	3,621 (17.3%)	1,840 (9%)	4,170 (20%)	20,953 (100%)

A further exploration of the 100-Car Study data illustrates that the travel pattern varies by occupation. The drivers from the 100-Car Study were divided into three groups according to their working statuses and associated driving needs: Non-workers (students, housewives, etc.); Shift workers (retail managers, nurses, carriers, etc.); and Regular workers (engineers, government employees, ministers, etc.). As can be seen in FIGURE 8, the more regular working hours a driver has the longer he/she drives. This difference caused by working status partially explains the large standard deviations introduced before and should be considered as one of the factors affecting EV designs.

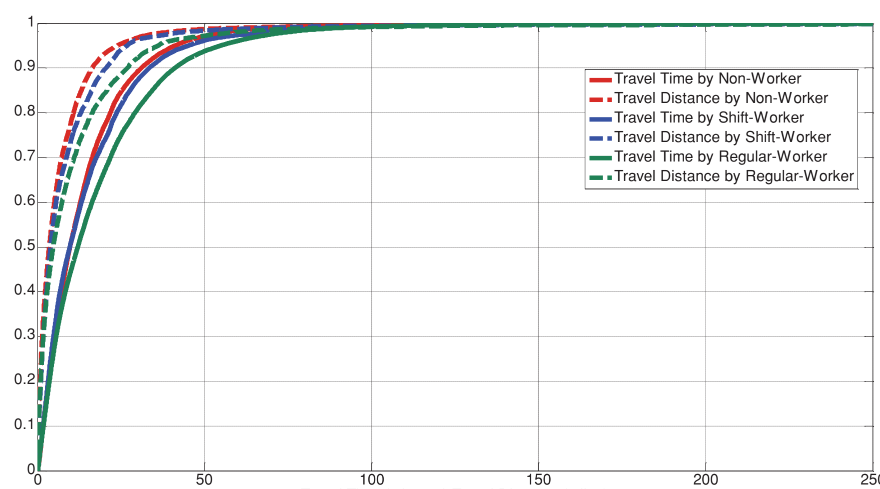


Figure 10. Different travel patterns of different driver categories.

The design of EVs should also take into consideration the road network attributes. The 100-Car Study data were collected within a relatively sprawling metropolitan area in which the distances to work of participants are greater than those experienced in suburban areas. The EVs should suit different travel environments in addition to the varied requirements from drivers.

7. COSTS OF TRIPS

The cost to generate electricity actually varies minute-by-minute. Key factors affecting the price of electricity include: Fuels; Power plants; Transmission and distribution lines; Weather conditions; and Regulations. Throughout a single day, the wholesale price of electricity on the electric power grid1 reflects the real-time demand for electricity. Demand is usually highest in the afternoon and early evening when usage is at a peak (so called "on-peak" hours) which means prices are higher at these times (*17*). It is recommended to recharge electric cars during night time to avoid overloading electrical grid and save the costs.

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